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Identification of Dangerous LNG Sloshing Using a Rapid Sloshing Model Validated with Computational Fluid Dynamics

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ABSTRACT

A non-linear pendulum model is developed to represent the motion of a sloshing fluid in real time. The forces imposed by the sloshing fluid are identified using multiphase RANS CFD simulations and subsequently included in the pendulum sloshing model. The pendulum sloshing model was used to simulate sloshing induced by linear and angular motions at and near resonance. Good agreement between the CFD data and the pendulum sloshing model was observed. A blind simulation with multiple surge excitation components is carried out and the pendulum sloshing model agrees with the RANS CFD result. Typically, the computational time of the pendulum is approximately 1/700th of real time.

KEY WORDS: Sloshing; multiphase; CFD; Simplified sloshing models; nonlinear pendulum

INTRODUCTION

Sloshing occurs when a tank is partially filled with a fluid and subjected to an external excitation force (Olsen, 1976). Ships with large ballast tanks and liquid bulk cargo carriers, such as very large crude carriers (VLCCs), are at risk of exposure to sloshing loads during their operational life (Rizzuto and Tedeschi, 1997). The inclusion of structural members within the tanks dampens the sloshing liquid sufficiently in all but the most severe cases. However, this approach is not used for Liquefied Natural Gas (LNG) carriers and the accurate calculation of the sloshing loads is an essential element of the LNG tank design process (Bass et al., 1980; Knaggs, 2006). Recent increases in vessel size have renewed interest in methodologies for the simulation of the sloshing loads experienced by the containment system (Han et al., 2005; Card and Lee, 2005).

While the sloshing response depends on the amplitude and frequency of the excitation force, history effects can be of significance as well. Waterhouse (1994) observed the hard and soft spring-type behavior of a sloshing flow. The offset of the response peak from the resonant excitation was found to depend on the tank filling level.

The work of Abramson (1966) summarizes the methods available in modern sloshing analysis, and Ibrahim (2005) gives an up-to-date survey of analytical and computational sloshing modeling techniques. A more general modeling technique is the solution of the Navier-Stokes equations using Computational Fluid Dynamics (CFD). Some recent examples of CFD sloshing simulation include Hadzic et al. (2002), Aliabadi et al. (2003), Standing et al. (2003) and El Moctar (2006).

Sloshing flows are treated as a transient problem in CFD. While the number of sloshing oscillations can vary, a large number of time steps, usually $O(10^2)$ to $O(10^3)$ per oscillation are required. Design optimization or the use of a numerical wave tank to gather statistical sloshing pressure data (Graczyk et al., 2006) require long simulation times or multiple runs.

The associated computational requirements make the use of a three dimensional CFD model impractical for such studies. There is still a requirement for the development of simplified mathematical sloshing models. These models operate in faster than real time (fast time) and can be used to provide sufficiently long time series for statistical analysis. Faltinsen et al. (2000, 2001, 2002) use a potential flow model and develop a multimodal system to describe sloshing in a rectangular container. Reported computational times for two dimensional sloshing are less than 1% of real time (Faltinsen et al., 2000).

Phenomenological modeling is another approach for the development of a simplified sloshing model. Rather than solving a detailed mathematical description of the flow, the forces acting on the system are approximated and included in a mathematical model. Schlee et al. (2005) proposed a MATLAB-based model to determine the characteristics of a pendulum sloshing model based on experimental data.

The approach adopted in this study is to analyze the detailed fluid loading occurring during sloshing based on a validated CFD sloshing model. This allows the construction of mathematical models for the individual force components and other associated terms. These are then incorporated in a pendulum sloshing model. This model is tested using regular linear excitations at and near resonance. Angular motions are then investigated. Finally, the blind simulation of sloshing with multiple simultaneous excitations presents a test of realistic motions.